20-4 SEISMIC RETROFIT GUIDELINES FOR BRIDGES IN CALIFORNIA

Introduction

Memo To Designers (MTD) 20-4 provides requirements and guidelines for the bridge seismic retrofitting policies and procedures used by Caltrans[1]. The primary philosophy and performance standard for retrofitting highway bridges in California is to prevent the structure from reaching the collapse limit state[2] for the "Design Earthquake"[3]. Where post event structural serviceability is a design requirement, MTD 20-4 does not apply, and a more conservative approach based on project specific performance standards must be followed. MTD 20-11 shall be used to establish this criterion. It should also be noted that these guidelines are only a minimum requirement, and that good engineering judgement must be exercised in order to ensure a structure's integrity following the "Design Earthquake". While this memo is intended to provide guidelines for retrofitting existing structures, it is not possible to anticipate every situation that may be encountered. Therefore, it is the Engineer's responsibility to accurately assess the performance of the existing structure, and to develop retrofit strategies that ensure the retrofitted structure meets the "No Collapse"[4] performance standard.

Background Work and Review

As a preliminary step in determining if a structure requires retrofit, the Engineer should verify existing conditions. This would include a review of all As-built plans including any previous retrofit work for the structure, checking Structure Maintenance and Investigations records, obtaining site seismicity and geological conditions, and visiting the site to compare As-built and current site (including traffic and utilities) conditions. When evaluating a state highway bridge,

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1. This memo is intended to apply to Ordinary Standard State and Local bridges. In cases where this memo does not apply, the Engineer is referred to MTD 20-1 and 20-11.
2. The collapse limit state is defined as the condition where any additional deformation will potentially render a bridge incapable of resisting the loads generated by its self-weight. The "No Collapse" performance standard prevents failure of this type while allowing for the possible localized failure of some individual components (typically redundant or secondary that are not necessary for structural stability).
3. The "Design Earthquake" is the collection of seismic hazards at the bridge site used in the design of bridges (defined in MTD 20-1) and includes those seismic hazards with a reasonable chance of occuring during a bridge's life. Ground motion hazards are determined from the "Design Spectrum" in Seismic Design Criteria (SDC) Section 2.1.
4. The goal of the "No Collapse" performance standard is to protect human life during the "Design Earthquake". However, serviceability following the event is not assured and the bridge may be so severely damaged that removal and replacement may be necessary.

the Engineer should also review the Structure Replacement and Improvement Needs Report (STRAIN) to assess the need to combine retrofit work with other work such as deck rehabilitation, barrier replacement, etc. wherever possible. This should be done as early in the project development phase as possible in order to properly scope the project.

Initial Assessment of Structure

Careful consideration should be given to assess the structural response of the entire system for the "Design Earthquake" in order to develop an effective seismic retrofit strategy. Prescribed processes may not apply to every situation. For example, yielding of a single element may not be sufficient to create a collapse mechanism. The redistribution of additional load in a structural system after incremental yielding will be different for each structure; therefore, each structure should be thoroughly evaluated. The Engineer should evaluate and retrofit the structure against all feasible collapse modes. An incremental approach for evaluating the level of retrofit necessary should be used for developing a retrofit strategy that achieves the most economical retrofit design while meeting the "No Collapse" performance standard.

The Engineer should initially develop a diagnostic model to analyze the structure in the As-built condition. It is essential that this step be performed even if there are obvious vulnerabilities in order to establish a benchmark of member demands. The purpose of this analysis is to evaluate the state of the structure and identify all possible collapse modes for the "Design Earthquake".

For modeling and analysis guidelines, the Engineer is referred to the Seismic Design Criteria (SDC), and in particular:

- Section 2.1.2 for horizontal ground motion combinations
- Section 2.1.5 for damping factors
- Section 5.1 – 5.5 for analytic methods
- Section 5.3 for global analysis modeling including bridges with irregular geometry
- Section 5.6.1 for effective section properties
- Section 7.8 for abutment response

Seismic load cases shall be combined with dead loads. Other loads may be applied per the procedure defined in MTD 20-11.

Initially, the Engineer should estimate various modeling parameters, such as abutment stiffness, cracked section properties, etc., and run a diagnostic model assuming structural integrity is maintained in order to establish initial demands. These resulting displacement demands are then compared with member capacities. Some of the Demand/Capacity ratios the Engineer should check include (but are not limited to) ultimate displacement, shear, pile capacities and seat length. The initial modeling assumptions, such as abutment stiffness, etc., used in the diagnostic model are then verified. If necessary, the model is rerun with revised assumptions, and then checked again. This process is repeated until results converge with the assumed modeling parameters.

Development of Retrofit Strategy

After the diagnostic model is completed and the collapse mechanism is identified, the Engineer should estimate the minimum amount of retrofit required[5] to meet the "No Collapse" performance standard. A diagnostic model with the proposed retrofit is then run. If a collapse mechanism for the structural system still exists, additional retrofit measures are required. If the retrofit model indicates there is no collapse mechanism and that the associated member demands are significantly less than their capacities, the Engineer should consider reducing the amount of retrofit and rerunning the model. This procedure is repeated until an optimal, or "preferred", retrofit strategy is obtained. Alternative retrofit strategies may also be considered as well. For each alternative, the Engineer should clearly demonstrate that the strategy is the minimum that meets the "No Collapse" performance standard. The Engineer should also develop sufficient conceptual details for the strategy in order to show that the strategy is feasible. Each strategy should address geotechnical, hydraulic, aesthetic, highway, environmental, constructability, utility and other relevant issues. During the strategy development phase, the Lead Office should consult with the Office of Earthquake Engineering (OEE) for complex strategies.

Following the development of the retrofit strategy, the respective Lead Office should schedule a Retrofit Strategy Meeting. Other relevant Functional Offices should be present at the meeting.

Lead Offices

- Offices of Structure Design North, Central, West, South 1 and South 2.
- Office of Special Funded Projects/Structures Local Assistance (OSFP/SLA)

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5. The minimum amount of retrofit is typically the retrofit alternative that satisfies the project report and environmental document and can be constructed for the lowest cost. Future maintenance costs should also be considered.

Functional Offices

- Earthquake Engineering
- Geotechnical Design Offices within Geotechnical Services
- Structure Design (for OSFP/SLA projects)
- Structure Maintenance and Investigations (as needed)
- Structure Office Engineer (as needed)
- Structure Construction (as needed)
- Bridge Architecture and Aesthetics (as needed)

The Lead Office should provide a Strategy Report to the meeting attendees at least one week prior to the Strategy Meeting. As a minimum, the report should include:

- A General Plan indicating the retrofit work for each alternative
- A summary of demand/capacity ratios (μ_D/μ_C), structural vulnerabilities, potential collapse mechanisms, and modeling assumptions for the diagnostic model and each retrofit alternative. If special retrofit requirements are a result of the findings of the Project Report or Environmental Document, they should be clearly shown in the Strategy Report
- Conceptual details that show the retrofit alternatives are feasible
- Relevant geotechnical information including soil types and potential for liquefaction
- Design spectrum and other earthquake hazards
- A cost estimate for each alternative

In addition, the Engineer should be prepared to discuss the analysis methods used to evaluate the existing structure as well as all retrofit alternatives.

While it is the responsibility of the Engineer to accurately assess the seismic performance of the existing structure, and to develop strategies that ensure the retrofitted structure meets the required performance standard[6], consensus on a final strategy should be obtained from the Strategy Meeting attendees. The Lead Office Chief will give final approval of the retrofit strategy and grant exceptions to retrofit requirements when necessary. After approval of the strategy is obtained, the Seismic Retrofit Assessment Form (Attachment A) should be completed by the Engineer and included in the Final Strategy Report. The Lead Office shall also submit a copy to the Chief, Office of Earthquake Engineering, for eventual incorporation into the permanent bridge records.[7] The Form may be found on the Office of Earthquake Engineering's Intranet web page.

6. The minimum required performance standard is "No Collapse" unless directed otherwise by the Lead Office Chief.

7. The purpose of the Seismic Retrofit Assessment form is to keep a record of previous seismic evaluations for future reference.

Structures may require seismic evaluation and retrofit when modified (widening, rehabilitation, etc.) as discussed in MTD 20-12 and 9-3. In these cases, the Strategy Meeting may be combined with the Type Selection Meeting (See MTD 1-29). The Engineer is required to demonstrate that the new or widened portion of the structure meets the SDC requirements while the combined structure meets the "No Collapse" performance standard. (See MTD 9-3 for additional guidelines and information). For complex strategies, the Lead Office may consider meeting with OEE prior to the Type Selection/Strategy Meeting in order to gain consensus on the recommended seismic retrofit strategies. In cases where there is an adjacent structure with potential seismic vulnerabilities similar to the bridge being modified (for example left and right bridges), it is important to ensure the adjacent structure is either retrofitted or programmed for future retrofit assessment. This may be accomplished by submitting a Seismic Retrofit Assessment Form (Attachment A) to the Office of Earthquake Engineering.

Retrofit Design Considerations

In order to assist in meeting the goal of the "No Collapse" performance standard, the Engineer should consider the most common vulnerabilities that may lead to collapse mechanisms and are described below.

Single Column Bents

Prior to 1971, single column bents were typically constructed by placing the footing with dowels protruding from the top of the footing. The column cage was then connected to the dowels by lap splices. These lap splices usually had insufficient length to maintain enough fixity to develop the plastic capacity of the column. Slippage of the lap splice may result in enough loss of fixity to compromise the overall stability of the structure. When retrofitting a column to maintain flexural capacity, the column's plastic moment will be transferred to the footing and consideration should be given to strengthening the footing in order to resist the resulting moment. However, rotation of a footing is not necessarily a collapse mechanism, and axial displacement of a pile through the soil will dissipate energy from the earthquake. Therefore, it may not be necessary to ensure fixity at every column/footing connection and slipping of the lap splices may be permitted provided the vertical load carrying capacity of the column is not compromised.

Multi-Column Bents

In multi-column bents, the columns are typically pinned at the base. In these cases there are no lap splices and moment is not transferred to the footing. However, if the column/footing connection is fixed, the Engineer should consider if the fixed condition is necessary for structural stability and take appropriate measures.

Foundations

Damage to abutment and footing piles is acceptable provided this does not lead to a potential collapse of the structure. In a pile type foundation, if a fixed condition is not required, foundation damage that could result in a substantial loss of fixity may be acceptable. However, there should be a sufficient number of piles in the resulting effective foundation region to maintain the stability of the structure. The effective foundation region is assumed to be an area bounded by the column and one half of the footing depth on either side of the column. Similarly for spread footings, the effective area under the column should be sufficient to maintain structural stability.

Pile Extensions

In the case of relatively short slab bridges (typically 4 spans or less) on pile extensions, the abutments typically provide most of the lateral resistance. The pile extensions may exceed their ultimate displacement capacities provided they maintain their vertical load carrying capacity. In general, vertical load capacity may be maintained up to a flexural ductility (Δ_D/Δ_y) ratio of 3.0 in these situations.

Transverse Reinforcement

Shear failures are brittle, and therefore the shear demand/capacity ratio should remain below 1.0. For structures with minimal and poorly detailed (#4 ties at 12 inches, or less) transverse reinforcement, the Engineer should assume that only the concrete provides shear resistance in these cases. For bridges that have improved transverse column reinforcement details, it may be assumed that both concrete and steel provide shear resistance. The shear capacity may be determined using expected As-built material properties combined with the methods described in SDC Section 3.6.

Abutments

On shorter bridges (typically 4 spans or less), the abutments may provide significant resistance to longitudinal movement. Using methods discussed in SDC Section 7.8.1, the Engineer may apply longitudinal abutment springs to structural models. Typically on seat type abutments, the shear keys and backwalls are designed to fail at events less than the "Design Earthquake".

Bent Caps

In bridges with multi-column bents, hinging may occur in the bent cap. While this is not desirable, it may not necessarily lead to a collapse of the structure. Hinging in the bent cap may be permitted provided the flexural ductility ratio is less than 2.0, and there is sufficient shear reinforcement in the cap to resist the dead load shear. At flexural ductility ratios above 2.0, the Engineer should demonstrate that the hinging does not form part of a collapse mechanism or take measures to ensure that collapse does not occur.

P-Δ Effects

For P-Δ effects in the transverse direction, when the requirements of the SDC Section 4.2 are exceeded, the Engineer should either demonstrate the structure still meets the "No Collapse" performance standard or take measures to address the vulnerability. For movements in the longitudinal direction, the soil mass behind the abutment may be sufficient to prevent additional movement caused by P-Δ (the soil mass acts as a restoring force).

Pier Walls

Pier walls should be analyzed as columns in the weak direction, and as a shear element in the strong direction. For bending in the weak direction, flexural ductilities less than 4.0 are permitted, while allowable shear forces would be the same as for columns. Damage to piles is acceptable provided the stability of the pier wall is not compromised.

Expansion Joints

On longer bridges with continuous superstructures, expansion hinges are used to allow for thermal expansion. The Engineer should ensure that the hinge has sufficient seat length to accommodate differential movements between adjacent frames for the "Design Earthquake". The SDC Section 7.2.5.4 provides guidance for determining adequate seat length, however, the 24 inch minimum seat length required by the SDC does not apply for retrofit. If the seat length is not adequate, the Engineer should take measures to ensure the hinge does not become unseated for the "Design Earthquake".

When in-span hinge seats are six inches or less, pipe seat extenders are required. In the case of in-span hinge seats between six and twelve inches, the seat should be retrofitted by some method (typically cable restrainers or pipe seat extenders), although pipe seat extenders are highly recommended.

When it is necessary to core through hinge diaphragms or bent caps in order to place pipe seat extenders or hinge restrainers, the Engineer is cautioned to avoid damaging structurally critical elements such as pre-stressing steel or shear reinforcement.

On some existing cable restrainer systems, the cables were grouted into the openings, essentially reducing the effective length of the cables to a just few inches. The Engineer should refer to the As-built plans to determine if the existing cables were grouted. The Engineer should consider that in a seismic event, grouted cable restrainers could fail at small movements thus leaving the hinge unrestrained, and therefore take appropriate measures such as pipe seat extenders.

Simple Spans

On bridges with simple span superstructures, the Engineer should ensure that the spans remain seated on the abutments and bents for the "Design Earthquake". Often, it is not practical to place pipe seat extenders in these situations. Catcher blocks and shear keys are an effective means of retrofit for these situations and typical details may be found in Bridge Design Aids (BDA) 14-5. Cable restrainers may also be used to prevent unseating of bridges with simple spans.

Rocker Bearings

On some structures, tall rocker bearings were used at the abutments and at the bent caps on simple span configurations. For the "Design Earthquake", these bearings could fail and result in a drop of the superstructure. While a drop of six inches or less is not typically catastrophic, a potential drop greater than this should be investigated in order to ensure that the structure is not vulnerable. When the height of the rocker bearing is greater than $^{2}/_{3}$ of the seat length, the superstructure could become unseated and the Engineer should consider appropriate retrofit measures.

Flared Columns on Multi-Column Bents

Flares on columns are an architectural feature on some bridges in California. It is desirable for plastic hinges to form at the top and bottom of the column as this minimizes its plastic shear and rotational demands. However, flares on multi-column bents typically cause a hinge to form at the base of the flare rather than at the top of the column thus increasing the column's plastic shear demand in the prismatic portion, and potentially exceeding its rotational capacity.

Liquefaction

Earthquake ground motions may cause liquefaction and thus reduce the lateral and vertical load carrying capacity of the soil. However, liquefaction may not necessarily cause a collapse of the structure provided it does not result in excessive settlement or rotation of the foundations. The Engineer shall determine if liquefaction leads to a potential collapse mechanism. If a potential collapse mechanism exists, either footing modification or soil improvement is usually required to meet the “No Collapse” performance standard. In these situations, the Engineer is referred to MTD 20-14 and 20-15 for guidance.

Joint Shear

Since the early 1990’s, greater emphasis has been placed on joint shear considerations in the seismic design of bridges. Previously, joints were modeled as either fixed or pinned if demands exceeded the elastic joint shear capacity. As a joint is cycled at high ductilities during a seismic event, it may degrade and lose some of its ability to carry moment and act as a rotational spring. Degradation models for modeling column/beam joints as a spring are available. A procedure and example for determining the effects of joint shear may be found in the BDA 14-4.

While joint shear is not typically a collapse mechanism and retrofit is not usually required, on long viaducts a large number of adjacent joints that form pins could potentially lead to instability of the structure. In these situations, with the concurrence of the Lead Office Chief, the Engineer shall demonstrate that a potential collapse mechanism exists and retrofit the minimum number of joints to ensure structural stability.

The procedure for determining joint shear on pre 1994 structures was developed from recently completed research (UC Berkeley report - “Effects of Local Deformations on Lateral Response of Bridge Frames”). The procedure may require modification as the knowledge base increases. Currently there are no proof tested methods of retrofitting for joint shear. The Lead Office shall obtain approval for the design and details for joint retrofit from OEE.

Common Retrofit Measures for Existing Bridges

Steel Column Casing

The most common column retrofit is to encase the column with a steel jacket to increase the confinement and to improve the flexural ductility and shear capacities of the columns. There are two classes of steel column casing retrofit currently in use, Class F and Class P/F. These types of casings should be circular for square and round columns, and elliptical for rectangular columns (refer to BDA 14-2 for casing and radius requirements). However, when retrofitting for shear only, it is not necessary to maintain a circular or elliptical shape. Flat plates may be used when required due to limited horizontal clearance.

In the Class F retrofit, no gap is provided in the space between the column and the steel casing resulting in full-length confinement of the column. This limits the dilation of the concrete and prevents lap splices from slipping thus ensuring the fixed condition of the column/footing connection remains intact. The supporting footing may require strengthening so that it is capacity protected by the column.

In the Class P/F retrofit, a gap between the column and steel casing is provided around the plastic hinge region near the bottom of the column. This allows the concrete to dilate and the lap splices to slip and ensures that a pin will form at the bottom of the column. The Class P/F column casing prevents the column's plastic moment from being transferred into the footing and should eliminate the need for footing retrofit. However, the column shear capacity in the lap splice region is limited to the capacity of the steel casing. Details for column casings (Both Class F and Class P/F) can be found in BDA 14-2 and the Standard Detail Sheet XS7-010.

Footings

When Class F column shells are used in single column bents, it is assumed that the footing (including pile caps) should resist the column's plastic moment[8]. For structures designed prior to 1971, the following vulnerabilities may exist in the footings:

- No top mat of reinforcing steel.
- Inadequate tension ties connecting the pile and the footing.
- Inadequate pile capacity for the column's plastic moment.
- Insufficient shear strength in the piles to resist the column's plastic shear.

Composite Column Casings

Occasionally, space or clearance considerations do not allow steel column casings to be used for retrofit. In some of these cases, Fiber Reinforced Polymer (FRP) composite jackets may be used instead. See BDA 14-3 for procedures and specifications when using this alternative.

In-Fill Walls

In multi-column bents, the in-fill wall is an inexpensive and effective retrofit for addressing transverse vulnerabilities both in the columns and in the bent cap. Research has shown that in-fill walls performed best when the concrete is placed directly against the soffit of the bent cap.

8. Typical details for a footing retrofit may be found in BDA 14-5.

Doweling into the soffit of the bent cap does not provide any additional capacity and thus is not recommended. Typical details for the in-fill wall may be found in BDA 14-5.

Abutment Strengthening

On short bridges, mobilizing the soil behind the abutments may be sufficient to reduce displacement demands below the structure's displacement capacity. This may be accomplished by strengthening the abutment diaphragm, or in the case of seat type abutments, connecting the superstructure end diaphragm to the seat. In some cases a large gap exists between the end diaphragm and the backwall in the As-built condition. In these cases the soil behind the backwall may be mobilized by eliminating the gap with concrete or timber blocking. The Engineer is cautioned to leave a gap that still allows for service load and temperature movements of the structure.

Catcher Blocks

Abutment bearings frequently fail during seismic events. However, such localized failure is not generally catastrophic unless the drop exceeds six inches. Seat catchers are an effective and inexpensive method of limiting superstructure drop and providing additional seat length as well. Catchers may also be used on bent caps for simply supported structures.

Cable Restrainers

On longer structures with expansion hinges, tying the frames together to limit differential displacement with cable restrainers may be an inexpensive and effective retrofit method in some circumstances[9]. Cable restrainers may also be effective in preventing unseating of simply supported bridge spans.

Pipe Seat Extenders

Pipe seat extenders are effective in preventing collapse of a hinge span; however, the bridge may not be serviceable when the hinge opens sufficiently to engage the extenders. Therefore when pipe seat extenders are used for retrofit, consideration should be given to placing cable restrainers through the pipe and anchoring them to the adjacent bent cap. This should limit the differential movement in the hinge during moderate events and reduce damage to the bearing pads and expansion joints.

9. Guidance for determining the type and number of restrainers may be found in BDA 14-1 and MTD 20-3.

The typical detail (found in BDA 14-5) for a pipe seat extender makes use of Pipe 8 xx-strong. It is Caltrans practice to use an allowable force of 100 kips per pipe. However, when space or other considerations limit the number of pipes that can be placed, a higher design capacity (not to exceed 180 kips per pipe) may be used if verified through analysis. The Engineer should also consider that on skewed bridges the pipe seat extenders may be subjected to transverse forces as the superstructure tends to rotate. Pipe seat extenders should be installed so that movement of the bridge under service conditions is not restricted (typically the extenders should be placed parallel to the girders). In addition, the Engineer should evaluate the capacity of the supporting hinge diaphragm.

Foundation Retrofit

Typically, footings are strengthened by the addition of a top mat of reinforcing steel and additional piles. Foundation retrofit is usually costly and careful consideration should be given to retrofitting only the minimum number required to meet the “No Collapse” performance standard. Typical details for footing retrofits may be found in BDA 14-5.

Flare Isolation

Isolating a column flare is an inexpensive and effective method of eliminating the potential hinge formation at the base of the flare. Flares may be isolated by cutting the flare steel. However, the Engineer should ensure that the steel being cut is not necessary for structural integrity, and in any case, the main column reinforcement shall not be cut or damaged. If the flare steel is main column reinforcement, other retrofit measures should be used. In addition to cutting the steel, the top four inches of concrete is removed back to the constant cross-section of the column in order to allow the top of the column to rotate freely. The removal of the concrete will increase the span length of the bent cap and the Engineer should ensure that the modified bent cap meets service load requirements.

Base Isolation

Occasionally, a situation is encountered where physical constraints prevent the use of more conventional measures for retrofitting the substructure of a bridge. In these cases base isolation may be used as an alternative method by reducing the seismic forces transmitted to the substructure from the superstructure thus reducing or eliminating the need for substructure retrofit. Base isolation may also be used when it is necessary to balance the mass/stiffness ratio of adjacent frames. However, when using base isolators, there should be sufficient clearance between the soffit of the superstructure and the top of the bent cap in order to place the isolators. In addition, the superstructure should be free to move a sufficient amount for the base isolators to be effective[10].

[10.] When using base isolation, the Engineer is referred to the AASHTO Guide Specifications for Base Isolation Design (1999).

Other

While these retrofit measures are the most commonly used by Caltrans, there are many other methods available to the Engineer for retrofitting highway structures. In developing alternative retrofit measures, the Engineer should ensure that these measures address the vulnerabilities identified in the diagnostic model, and that the retrofitted structure meets the "No Collapse" performance standard. See BDA 14-5 for common seismic vulnerabilities and typical details for common seismic retrofits.

References

1. California Department of Transportation, Seismic Design Criteria Version 1.5
2. California Department of Transportation, Bridge Memo To Designers 9-3, 1-29, 20-1, 20-3, 20-11, 20-12, 20-14 and 20-15

5. AASHTO Guide Specifications for Base Isolation Design (1999)

4. California Department of Transportation, Bridge Design Aids 14-1, 14-2 14-3,14-4 and 14-5.
5. California Department of Transportation, Bridge Standard Detail Sheet XS7-010
6. UC Berkeley Report - "Effects of Local Deformation Material Response of Bridge Frames"

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